

White Paper

NEH Sustaining Cultural Heritage Collections Grant PF-230208-15

Replacement and Upgrading of HVAC Mechanical and Control Systems Serving the Art Museums of Colonial Williamsburg

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This project achieved the objective of extending the useful life and improving function of the HVAC mechanical system that sustains environmental conditions essential to the preservation of collections exhibited and stored at the Art Museums of Colonial Williamsburg. Primary project activities were to replace obsolete control systems, upgrade air handling systems, and evaluate means of saving energy while continuing to maintain an excellent preservation environment.

Improvements were implemented as described in the grant application Work Plan. Project progress and plan direction was communicated in interim performance reports. The in-depth Commissioning process identified many opportunities for improved performance. These were evaluated to determine which items would have greatest impact, and resources directed accordingly.

Project Activities

Controls Upgrade

The Building Automation System (BAS) controls upgrade was a significant undertaking, and essential to continued operation of the HVAC equipment. We replaced outdated Johnson Controls Inc. (JCI) controls with up to date generation JCI BAS throughout the museum, including Dewitt Wallace Decorative Arts Museum (DWDAM), Abby Aldrich Rockefeller Folk Art Museum (AARFAM), and Public Hospital (PH). Upgrades for each of the three museum areas' controls were awarded under separate contracts and phases with JCI. Common scope elements in each of these contracts included:

- Existing Metasys Control System was replaced with a new Open Architecture system using BACnet controllers, existing network controllers, and a web-based Front-End Interface, taking advantage of the existing shared LAN network, as well as the flexibility of using existing PC's on the network with security rights access to the system.
- Air Handler Unit (AHU) controllers were upgraded to new BACnet FAC3611 and IOM4711 controllers with remote mounted display for ease in viewing and editing parameters of the respective fan systems. The new controllers were installed in existing enclosures, the existing N2 bus was reused for the new FAC controllers, and a new bus was installed for the IOM expansion modules.

- Variable air volume (VAV) controllers were upgraded to new BACnet VMA1832 controllers and new discharge air sensors were installed for each. The existing N2 bus was reused for these controllers, and existing zone temperature/RH sensors were reused.
- Preparation for field work included: building and pre-wiring all panels,, backup of all existing controller databases, backup of front end software, roughing-in all wiring modifications, testing and verification of all existing wiring from existing controllers to all end devices, and identification and documentation of all end device types and characteristics, including sensor and actuator ranges, signaling, and physical locations.
- Programming and Installation included: writing the sequence of operation, developing programming applications for all controllers, entering and loading programs into processors prior to delivery onsite, installing controllers and terminating wiring, powering up processors and testing communications for all Ethernet network nodes.
- Network Installation and System Verification, including: connecting transmission trunk to the LAN network, setting up all communications parameters for the server and the controllers, installing the new BACnet Bus to all field controllers, testing communications with all nodes, testing communications with all AHU and VAV controllers, verifying operations and performance including commissioning agent support, and developing user-friendly graphics populated with real-time data.

During the commissioning process, many items for corrective action were identified. Items which could be corrected with minimal effort, such as calibrations and adjustments, were performed without further consideration. Items requiring more resources to correct were evaluated, and we performed the highest in priority in order to control project expenditures. Included in this category was the decision to install airflow measuring stations (AFMS) at the fan inlets of both supply fans (ACS-1 and ACS-2) and return fans (ACR-1 and ACR-2) at the DWDAM. The consensus between owner, commissioning agent, and controls contractor was that direct measurements of total supply air and return air delivered to and from the space was the preferred approach to controlling airflow and building pressurization.

A summary of “DWDAM & AARFAM Commissioning Action Items” we selected to implement is as follows:

AARFAM AHU-5

- Item 008: Relocate low duct static pressure safety – relocate tubing to fan side of duct.
- Item 009: High duct static pressure safety – program a time delay off to close AO point in DX for isolation dampers.
- Item 010: Return smoke isolation damper operation – reprogram sequence so that both end switches have to make before either fan runs (delay close).
- Item 013: Return fan operates when supply fan shuts down – reprogram interlock so that fans shutdown commanded off.

- Item 024: Interlock supply and return fan operation with supply and return isolation dampers – wire new interlocks with safeties.
- Item 025: Wire new interlocks with safeties to prevent manual operation of supply and return fans.
- Item 027: Humidifier enable point – delete from software and as-built.
- Provide setup, calibration, validation and checkout of systems with commissioning agent.

AARFAM AHU-4

- Item 023: Relocate low duct static pressure safety – relocate tubing to fan side of duct.
- Item 021: High duct static pressure safety – program a time delay off to close AO point in DX for isolation dampers.
- Item 016: Return smoke isolation damper operation – reprogram sequence so that both end switches have to make before either fan runs (delay close).
- Item 013: Return fan operates when supply fan shuts down – reprogram interlock so that fans shutdown commanded off.
- Item 024: Interlock supply and return fan operation with supply and return isolation dampers – wire new interlocks with safeties.
- Item 026: Wire new interlocks with safeties to prevent manual operation of supply and return fans.
- Item 027: Humidifier enable point – delete from software and as-built.
- Provide setup, calibration, validation and checkout of systems with commissioning agent.

DWDAM ACS-1

- Item 042: ACS-1 demo high static pressure switch.
- Item 047: Preheat steam valves – furnish and install two (2) new steam valves and actuators.
- Item 055: Supply air isolation damper end switch – replace and rewire the end switch.
- Item 064: Furnish and install new building static pressure sensor and wire to existing controller.
- Item 064: Furnish and install new air flow measuring station (AFMS) on supply and return fans – wire to new IOM4711 controller located in existing enclosure.
- Programming of system as required.
- Provide setup, calibration, validation and checkout of systems with commissioning agent.

DWDAM ACS-2

- Item 033: Preheat steam valves – furnish and install two (2) new steam valves and actuators.
- Item 035: Low limit thermostat – replace low limit.
- Item 039: Return fan discharge air damper – replace damper.
- Item 041: Low static pressure switch – hard wire the low static pressure switch to supply fan.
- Item 042: Demo high static pressure switch.

- Item 064: Furnish and install new building static pressure sensor and wire to existing controller.
- Programming of system as required.
- Provide setup, calibration, validation and checkout of systems with commissioning agent.

As work progressed, the following additional high priority controls improvements were added:

DWDAM ACS-1: Furnish and install electronic actuator M9220-GGA-3 for the minimum outside air damper. Demo and dispose of the existing pneumatic actuator.

DWDAM ACS-2: Furnish and install electronic actuator M9220-GGA-3 for the minimum outside air damper. Demo and dispose of the existing pneumatic actuator.

Public Hospital ACS-3: Furnish and install new ANSSA-012X036 airflow measuring station (AFMS) in the minimum outside air duct, wire to spare input on the IOM4710, setup and checkout. Demo and dispose of the existing AFMS.

The other JCI measure implemented in this project was replacement of JCI's Energy Dashboard and Reports Tool (EDART) software with JCI's Facility Performance Indicator (FPi) software. JCI advised they were discontinuing support of the EDART software and recommended we install its new FPi software. The software implementation and training was procured, including migration of existing data from EDART to FPi.

The AFMS for measuring outside airflow to AARFAM's AHU 4 and 5 was installed as part of our museum expansion project, which ran concurrently with this NEH supported project and will be completed next spring. Calibration and commissioning of this AFMS will be performed by the end of 2019. We did not replace the existing AFMS under the NEH project because a new outside air duct with AFMS was included in the scope of the museum expansion. The arrangement of the new outside air duct, with the desired straight section of ducting, provides an improved condition for uniform airflow across the AFMS and much better accuracy.

AHU Variable Frequency Drive (VFD) Conversions

In accordance with the Work Plan, VFD's were installed on AARFAM AHU-4 and AHU-5 prior to the grant period. This work was self-performed by CWF's Facilities Maintenance (FM) staff. The VFD's replaced the conventional "across the line" starters to remedy our recurring problem of premature belt failures that occurred due to the hard starts. Retrofitting to the "soft start" VFD's created the opportunity to experiment with and possibly implement night shut downs without creating belt failures that would have occurred if performing daily starts with the former conventional starter.

Replacement of the inlet vane dampers with VFD's for the DWDAM air handling units was completed by CST Mechanical as described below:

- Replaced existing 75 HP motors with Inverter Duty premium efficiency motors on ACS-1 and ACS-2, and replaced existing 20 HP motors with Inverter Duty premium efficiency motors on ACR-1 and ACR-2.
- Installed Toshiba Model Q9 VFD's for each of (4) fan motors described above and associated wire/conduit.
- Removed the double inlet fan vortex dampers on four fans (two 75HP, two 20HP).
- Furnished and installed new fan and motor sheaves, and new belts.
- Subcontracted with controls contractor JCI to interface the VFD's with the BAS.

Replacement of the inlet vane dampers with VFD's for the Public Hospital air handling units ACS-3 and ACR-3 were completed by CWF FM. As reported in our 2018 interim report, ACS-3 experienced a duct support failure in July 2018. This stressed the fan housing and caused damage to the fan support structure and fan shaft. The following scope of work was performed by CWF FM:

- Replaced existing 20 HP motor with Inverter duty premium efficiency motor on ACS-3 and replaced existing 7.5 HP motor with Inverter duty premium efficiency motors on ACR-3.
- Installed Toshiba Model Q9 VFD's for each of the 2 fan motors described above and associated wire/conduit.
- Removed the single inlet fan vortex dampers on two fans (20HP and 7.5HP).
- Re-support supply air duct and reinforce fan housing with welded steel channel supports.
- Procured a new fan shaft and balanced the existing fan wheel on the new shaft at machine shop.
- Reassembled fan and shaft with new bearings into fan cabinet.
- Installed new fan and motor sheaves, and new belts.
- JCI interfaced the VFD's with the BAS.

Additional ACS-3 Repair Scope

Evaluation of ACS-3 also led to a decision to replace the chilled water coil, extending the life of the 33 year old air handler. The steam coil had already been replaced a few years ago. The scope of this work, performed by Southern Air Inc. was as follows:

- Replaced chilled water coil (In-kind) in existing Carrier 39ED-26 Air Handling Unit.
- Provided all labor and materials necessary for chilled water coil replacement, including removing the chilled water supply and return pipe and valves to provide clear pull space for coil and reconnection using existing valves and new piping as required.
- Provided new gate valves to replace existing for coil drain and vent piping.
- Provided new pipe, fitting, and valve insulation for all chilled water supply and return piping located below top of air handler.
- Assisted CWF FM with venting new coil and putting back into service.

Commissioning Services

The commissioning process for the project was designed to validate the operation VFD's, BAS controls, and sequences of operation of the air handling units. Commissioning services were performed by Facility Dynamics Engineering (FDE). The Summary Commissioning Report was issued on June 30, 2019. Installation Verification and Functional Performance Testing (FPT) was performed on the following systems:

- Air Handling Units ACS-1 & 2 and Return Fans ACR-1 & 2 serving the Dewitt Wallace Decorative Arts Museum (DWDAM).
- Air Handling Unit ACS-3 and Return Fan ACR-3 serving the Public Hospital (PH).
- Air Handling Units AHU-4 & AHU-5 serving the Abby Aldrich Rockefeller Folk Art Museum (AARFAM).

A total of 324 Functional Performance Tests (FPT's) were performed. The breakdown of the test results were as follows:

- 210 tests passed
- 93 items required further action/correction and were resolved
- 13 items open resolve at commissioning summary report (10 underway, 3 future)
- 8 items open recommend at commissioning summary report (8 future)

These results demonstrate the value of the commissioning effort, achieving 94% pass on FPT's at time commissioning summary report was drafted, and anticipating 97% pass on FPT's when the 10 additional action items underway are completed, at which time release of final payment to JCI will be made. Eleven remaining items that were identified during the commissioning process were deferred for future consideration.

One item that the commissioning agent investigated during testing was that ACS-1 flows less air volume than ACS-2. Both units are operated in parallel, with common fan speed signals sent to each supply fan VFD. They verified each units' performance and the reasonable (within 10% of measured) calibration of the new supply air flow measuring stations (AFMS). The testing results and unit data were provided in the summary report and are included as Table 1- DWDAM ACS-1 & 2 AIRFLOW TEST (see page 9). The conclusion was that the supply duct geometry restricts supply air from ACS-1. This additional information provided by the AFMS will be helpful to understand and diagnose future performance of these individual air handlers.

The commissioning agent concluded that the building is operational and occupied with the exception of portions associated with the museum expansion construction project. Commissioning functional testing is complete as well as the resolution of the majority of the action items. There are no open action items that the CA considered to have any impact on Life Safety, and none with significant impact on energy or environment.

Accomplishments, Evaluation, and Continuation of the Project

Observations of VFD Energy Savings

Electrical energy usage of the large DWDAM air handlers ACS-1 & 2 supply fans (75 HP each) and associated return fans ACR-1 & 2 (20 HP each), was determined by evaluating metered data of these fans both before and after the inlet vane vortex dampers were replaced with VFD's.

The analysis of the data revealed some discrepancies in the metered data, JCI's EDART database, and their upgraded EDART replacement FPi data base. After reconciling the data to the extent possible, we observed that VFD's on the supply fans had little to no impact on energy consumption and concluded that the vortex inlet vanes achieved efficiencies similar to those achieved with the VFD's. Evaluation of return fan energy suggest energy reductions approaching 60 percent, or approximately \$6,500 per year. The reduced energy is a result of installing airflow measuring stations (AFMS) on both the supply and return fans and controlling the return fans to a supply/return offset CFM. Previously, return fans were controlled to the same signal as the supply fans. This new control strategy has decreased return airflows and associated fan energy.

The process of metered data evaluation began with a review of JCI's FPi software which was installed in May 2019. It became apparent that energy data analysis using this software would be time consuming and require further support from JCI to develop energy report applications to readily retrieve and present findings. As such, we reverted to using JCI's EDART software. JCI had previously advised us they would be discontinuing support of EDART, and recommended we migrate to FPi, which we did. Nevertheless, even without JCI support, we found EDART energy analytics package more useful for this effort.

The monthly electrical energy consumption for DWDAM air handlers is shown in Table 2 through Table 5 (see p. 10 - 13) for years 2016 through 2019. The following provides further explanation:

Table 2: DWDAM Fan Energy 2016. Note that the meters were installed and began recording on September 12, 2016. As such data shown for September is a partial month. Data analysis also discovered that EDART software was incorrectly calculating KWH. This is further explained in review of Table 6.

Table 3: DWDAM Fan Energy 2017. Data analysis determined that KWH calculation was corrected effective with the June 2017 data and thereafter. Also of interest is the July through December consumption showing ACS-1 using significantly more energy than ACS-2. We have concluded the meter inputs to the BAS were reversed (ACS-2 actually used more energy).

Table 4: DWDAM Fan Energy 2018: VFD's went on line in mid-January. Subsequently, it was discovered that the current transformers (CT's) were installed on the load side of the VFD. This caused the meters

to record the power incorrectly, thus the lack of data through August. After identifying the problem, the meters were installed on the line side of the VFD's and correct data was established September and thereafter. Note also that the inputs were corrected to show ACS-2 as the greater energy load.

Table 5: DWDAM Fan Energy 2019: Note that October is only a partial month of data. Also, note the extremely low energy consumption of RS-1. This is the return fan for ACS-1. This is an abnormal situation likely caused by a malfunctioning AFMS for ACS-1. The low airflow measurement of ACS-1 is causing the return fan to reduce to minimum speed to control the return airflow with an offset relative to the supply airflow. Corrective action to troubleshoot and repair is scheduled.

A comparison of the supply fan energy before and after installation of the VFD's is shown in Table 6 (see p. 14). The first comparisons selected October as a month where reliable data was available for all four years (used September in 2019 as October was partial data month). The comparison shows a 12 to 14 percent energy reduction from October 2016 (Inlet Vanes) to October 2018 (VFD's). The comparison from October 2017 (inlet vanes) to October 2019 (VFD's) shows essentially no savings. Additional comparisons of July and August 2017 (inlet vanes) to July and August 2019 (VFD's) show no savings. Thus the conclusion that replacing the inlet vanes with VFD's provided little to no energy savings.

A comparison of the return fan energy before and after installation of the VFD's is shown in Table 7 (see p. 15). The comparisons selected October as a month where reliable data was available for all four years (used September in 2019 as October was partial data month). The comparison shows an approximate 32 to 44 percent energy reduction from October 2016 and 2017 (Inlet Vanes) to October 2018 (VFD's). After the AFMS's were installed and the VFD's controlled to an airflow offset to the supply airflow, the reduction for RS-2 from October 2016/2017 average consumption to September 2019 consumption was 61% (3,897 KWH). As described previously, RS-1 September 2019 data is abnormal due to a suspected malfunction of SA AFMS causing the return fan to run at minimal speed. Once corrected, energy performance is expected to be similar to RS-2.

Observations of AHU Shut-Downs

We experimented with several overnight (10PM to 7 AM) shutdowns of AARFAM AHU 4 and 5 in order to evaluate changes in conditions. Data tracked with loggers that have been in place since 2014 indicated that temperature rose very slightly, 1-2 degrees, over this period. Relative Humidity was virtually unchanged.

As previously mentioned, we began construction of a 65,000 square foot addition along the south wall of the DWDAM and AARFAM sections of the museum in the fall of 2017. This required penetration of the robust, insulated building fabric in order to create 4 large portals (temporarily filled with plywood and insulation) between the new and old building. Mechanical and electrical work relating to this construction have required numerous shut-downs of all 5 AHU's that are part of this project. Each time shut downs were performed we evaluated results. The impact on the collections' environment is

minimal when kept to 12 hours or less. This indicates that once construction is finished our HVAC programming will be able to eliminate use of HVAC equipment for at least 9 hours each day.

Once commissioning of new HVAC equipment is complete and portals between sections are permanently opened we will test further in hopes of using similar programming for HVAC in the new addition.

Long Term Impact

Replacement and Upgrading of HVAC Mechanical and Control Systems Serving the Art Museums of Colonial Williamsburg has served to modernize and extend the useful life of 5 very large air handlers that will continue to provide excellent collections' environment for years to come. It allows the controls system for this equipment to be seamlessly integrated into a larger, comprehensive mechanical controls and monitoring system for CW's entire museums complex. The VFD and fan upgrades allow for safely implementing routine shut downs, which will save energy and extend equipment life.

At the end of 2019 these air handlers will be supplied by chilled water, hot water and steam generated in an entirely new mechanical plant and controlled by a state of the art BAS - part of our 65,000 square foot, 42 million dollar museum expansion and renovation project that will add 22% more exhibition space. Implementing the NEH Sustaining Cultural Heritage project in parallel with planning and construction has been extremely beneficial. Many of our observations of actual conditions and operations informed design decisions and will help us start out with most efficient energy use in our new collections areas.

Table 1 - DWDAM ACS-1 & 2 AIRFLOW TEST

DWDAM ACS-1 & 2 SA Flow Test
May 15 2019
D. Coleman

ACS	SA Fan Static Press inwg			VFD Data				Motor rpm	Fan rpm	Airflow cfm					Comparison AFMS/FDE
	Suction	Discharge	TSP	Hz	amps	%motor load	kw			Fan Curve	Measured (by FDE) avg fpm	cfm	AFMS	BAS	
1	-0.57	0.18	0.75	20	19.6	25	1.3	593	341	~1000	150	8535	0	36	Note 2
	-1.11	0.53	1.6	30	26.5	29	4.7	890	512	~20000	255	14510	13100	13400	90.3%
	Note 1		5.6	60	49.6	54	26.1	1780	1024	45000	424	24126	26000	26747	107.8%
	-2.8	3.4	6.3	59.7	59	66	35						25400	26580	
2	-0.6	0.16	0.75	20	20.1	25	1.5	593	341	~1000	155	8820	4400 to 8800	6966	Note 3
	-1.2	0.44	1.66	30	27.4	31	5	890	512	~20000	265	15079	14700	15600	97.5%
	-2.9	3.6	6.5	60	66.5	76	40.5	1780	1024	40000	547	31124	32300	35800	103.8%

Notes:

- 1 Failed to record suction and discharge pressures at 60 hz test. Recorded later at 59.7hz
- 2 AFMS does not read low flow well
- 3 AFMS varied as if fan was surging, but no physical attributes (noise, changing air velocity, etc) were present when measuring the airflow. Fan curve is very flat in this operating range.
- 4 Fan speed calculated using sheave pitch diameter ratio only. No allowance used for motor slip.

ACS-1 & 2

Sheave	PD	Ratio
Motor	5R5V92	9.15
Fan	5R5V160	15.9
V-belts	5V1320	

Motor rpm	Nameplate	sync	slip
1780	1800	0.011111	



Universal Dashboard

DWG

TABLE 2
DWDAM FAN ENERGY 2016



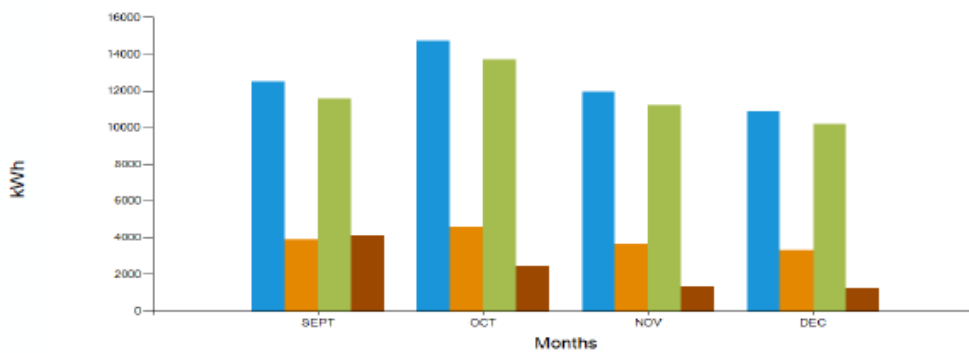
Facility : DWG

Building : DWMDAM

Energy => Energy Performance Dashboard => MONTHLY CONSUMPTION

Monthly Universal Dashboard For : 2016

Universal Dashboard



Y1 Axis Legends

- ACS1
- RS1
- ACS2
- RS2



Universal Dashboard

DWG

TABLE 3
DWDAM FAN ENERGY 2017



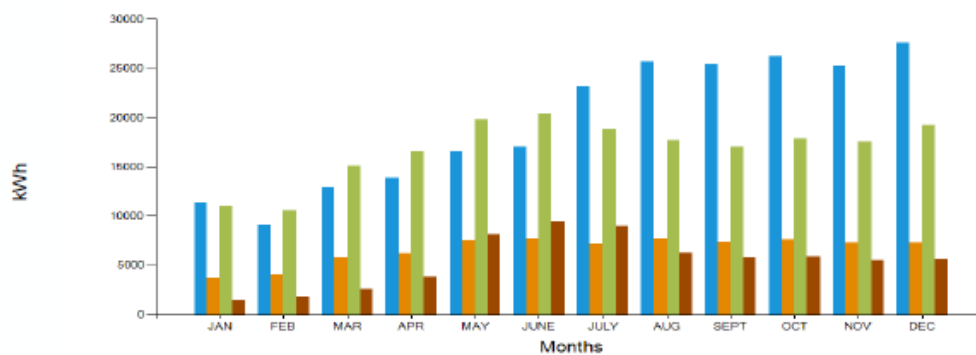
Facility : DWG

Building : DWMDAM

Energy => Energy Performance Dashboard => MONTHLY CONSUMPTION

Monthly Universal Dashboard For : 2017

Universal Dashboard



Y1 Axis Legends

- ACS1
- RS1
- ACS2
- RS2



Universal Dashboard DWG

TABLE 4
DWDAM FAN ENERGY 2018



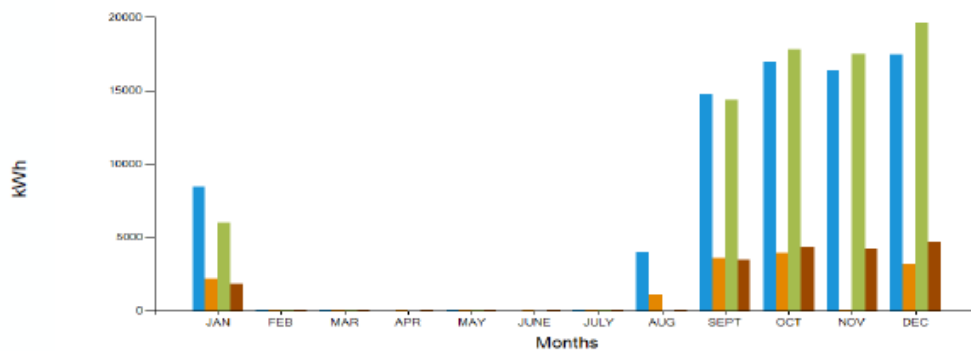
Facility : DWG

Building : DWMDAM

Energy => Energy Performance Dashboard => MONTHLY CONSUMPTION

Monthly Universal Dashboard For : 2018

Universal Dashboard



Y1 Axis Legends

- ACS1
- RS1
- ACS2
- RS2



Universal Dashboard DWG

TABLE 5
DWDAM FAN ENERGY 2019



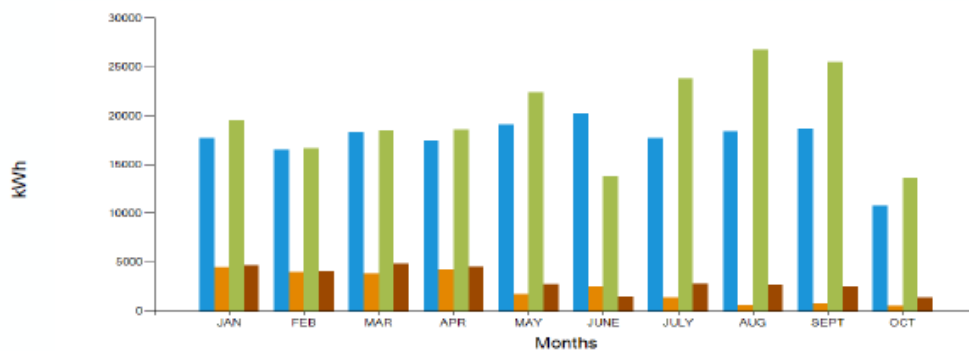
Facility : DWG

Building : DWMDAM

Energy => Energy Performance Dashboard => MONTHLY CONSUMPTION

Monthly Universal Dashboard For : 2019

Universal Dashboard



Y1 Axis Legends

- ACS1
- RS1
- ACS2
- RS2

**TABLE 6 - Energy Comparison Inlet Vanes vs. VFD
DWDAM ACS-1, ACS-2**

<u>Month/Year</u>	<u>ACS-1 (KWH)</u>	<u>ACS-2 (KWH)</u>	<u>Notes</u>
2016 (October)	19,286	20,688	1,2,3
2017 (October)	17,852	26,287	1,2
2018 (October)	16,931	17,801	4
2019 (September)	18,631	25,479	4

Notes:

1. Operating with Inlet Vanes
2. Meter input to BAS swapped between ACS-1 and ACS-2, data adjusted correct assignment
3. KWH calcs in EDART corrected: Avg Daily Demand KW x 24 Hr = Daily KWH
4. Operating with VFD's

Additional Comparisons

<u>Month/Year</u>	<u>ACS-1 (KWH)</u>	<u>ACS-2 (KWH)</u>	<u>Notes</u>
2017 (July)	18,897	22,184	Inlet Vanes
2019 (July)	17,722	23,837	VFD
2017 (August)	17,765	25,710	Inlet Vanes
2019 (August)	18,434	26,813	VFD

TABLE 7 - Energy Comparison Inlet Vanes vs. VFD
DWDAM RS-1, RS-2

<u>Month/Year</u>	<u>RS-1 (KWH)</u>	<u>RS-2 (KWH)</u>	<u>Notes</u>
2016 (October)	6,455	6,848	1,2,
2017 (October)	7,582	5,869	1
2018 (October)	3,930	4,297	3
2019 (September)	730	2,462	3,4

Notes:

1. Operating with Inlet Vanes
2. KWH calcs in EDART corrected: Avg Daily Demand KW x 24 Hr = Daily KWH
3. Operating with VFD's
4. RS-1 abnormal operation at 20 HZ due to suspected AFMS malfunction